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CONTINUOUS OPERATION OF A BALL DRYER

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The operation of a Precision Drying Systems Model 25N ball dryer was optimized for drying frozen vegetable products. The system was fully characterized by completing material and energy balances. The energy was balanced to 95%, including losses dues to air leakage, free convection and radiation. The maximum drying capacity of the system is 6.8 kg (15.0 lb) water removed from the carrots per hour, or 8.6 kg (18.9 lb) carrot dried per hour from 89 to 10% moisture. The practical conditions to preclude operational difficulties were identified. The ball screw speed was fixed at 1.2 RPM to maximize residence time. The maximum inlet temperature is limited to 110 C (230 F) due to ambient humidity. The feed rate must be less than 96 g (0.21 lb) per min to prevent clogging. A factorial designed set of experiments was performed to develop an empirical drying model based on inlet temperature, feed rate and exhaust valve opening. The model predicts percent water removal for diced carrots to within 2%. The model was extended successfully to whole peas and diced potatoes. Measured dependent properties included final percent moisture, total rate of water removal, rehydration ratio and color. Quality was found to suffer when the final moisture content was less than 15% moisture and freeze-drying as the second stage to 2% moisture. An economic analysis of this process shows a 70% decrease in utility costs as compared to freeze-drying alone.

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF TABLES

PREFACE

This study was undertaken during August 1994 at t he U.S. Army Soldier Systems Command, Natick Research, Development and Engineering Center, Natick MA. The funding was FTBB1313, Project ID: TB-PST.

We would like to thank our sponsors for all their help and advice. Lin Hallberg, always a source of insight and encouragement, even as she finished her own dissertation. Harry Dostourian, a great source of advice on mechanical issues which came up throughout the project. Joe Cohen, who helped us with our statistical analysis of the data, providing us with JMP™ software to visualize our data. We would also like to thank Mark Smith for providing our analytical instruments and Wayne Dimitri for helping us around the lab, especially with the freeze-dryer runs. Thanks to Dr. Ann Barrett for the use of the texture analysis equipment. Finally, we would like to thank everyone in the food engineering lab for their help.

Citation of trade names in this report does not constitute an offical endorsement of the product.

LIST OF ABBREVIATIONS

"a"	Color red/green hue
"b"	Color blue/yellow hue
ß	Model coefficients
C_S	Humid heat of air/water vapor mixture
F	Product Feed Rate
H	Absolute Humidity
k_{VC}	Ratio of drying rate of another vegetable to that of carrots
"L"	Color lightness value
M	Mass flow
μ	Viscosity of fluid
μ_S	Viscosity of solid
Nu	Nusselt number
O	Outlet exhaust valve position
Pr	Prandtl number
Q	Heat flow
Re	Reynolds number
T	Temperature
V_H	Volumetric Flow Rate
V_m	Mass Flow Rate
x_i	Model input variables
y_i	Model output variables

CONTINUOUS OPERATION OF A BALL DRYER

Summary

Dried foods are widely used in military rations to reduce weight and prolong shelf-life, while trying to retain sensory and nutritional properties. A Precision Drying Systems Model 25N™ ball dryer was used in this project to produce dried food products on a continuous basis for investigation. The first step was characterization of the dryer using material and energy balances for both empty and steady-state drying operation. The overall energy loss of the system was estimated to be 3.2 kW or 30% of the total energy input. The energy was balanced to 95% including losses due to air leakage, free convection and radiation. The maximum drying capacity of the system, based on actual operating conditions, is 6.8 kg (15.0 lb) of ice, at -15 C (+5 F), removed per hour. This is equivalent to drying 8.6 kg (18.9 lb) of frozen carrots per hour from 89 to 10% water content.

Optimization of operating conditions was based on maximizing drying performance within several practical limitations. The ball screw speed was held constant at 1.2 RPM to maximize the size and density of the food particles. The product feed rate did not exceed 96 g (0.21 lb) per min to avoid feed clogs and overloading of the hopper. The maximum attainable inlet temperature was limited to 110 C (230 F) due to the relative humidity. Opening the main exhaust valve increased the air velocity through the drying bed, thereby increasing the mass transfer coefficient of water through the product.

A factorial designed set of experiments was performed to develop an empirical drying model as a function of inlet temperature, feed rate and exhaust valve position. The model first tested all combinations of the parameters including interactions. The best fit was obtained using a model of only the main effects. This model included the valve position to the 0.5 power as suggested by the velocity dependence of convective heat and mass transfer coefficients. The model predicted the percent moisture removal for diced carrots to within 2%. (In this report, water and moisture are used synonymously.) The model was successfully applied to whole peas and carrots by using the ratio of drying rates from the moisture analyzer. The predictability of the model for potatoes was within 7% of the experimental results, while it predicted drying of peas to within 20 to 30%.

The product quality was assessed by measuring the percent moisture, rehydration, color and texture. Overall quality was found to suffer when the product was dried to less than 15% moisture. The only quality parameter found to correlate with operating variables was the lightness parameter of the color measurement. The model predicts that the dry product will become darker at higher temperatures.

Initial results suggest that products from the ball dryer are best suited for use in intermediate applications such as stew and soup. A formal sensory evaluation is

required to determine possible uses of the product. Economic analysis of a two-step drying process (ball drying followed by freeze drying) shows a 70% decrease in utility costs when compared to freeze-drying alone. Utility savings may be offset by capital costs and increased processing costs, so the viability of this process depends on the capacity of the equipment.

Introduction

Background

Dried vegetables are an important component of military rations, which are developed at the U.S. Army, Soldier Systems Command (SSCOM) Natick RD&E Center. (NRDEC) Drying significantly reduces ration weight and prolongs shelf-life, while retaining the flavor and nutritional properties of the food. The current drying method uses freeze-drying which is expensive and time-consuming. The use of a ball drying system is being investigated as a lower cost substitute for freeze-drying, but several problems have prevented utilization of the equipment. Problems include crushing of the product during feeding to the equipment and the drying process, as well as insufficient drying relative to the military specification requirement of 3% moisture. (MIL SPEC, 1983). To date, the ball dryer has been operated as a batch process to avoid feed damage, significantly reducing the production capacity of the equipment. The ball dryer is currently being considered for use either as a primary drying operation or as the first stage of a two-step drying process. Freeze-drying would be used to obtain the finished product.

A schematic diagram of the Precision Drying Systems Model 25N™ ball dryer system is shown in Figure 1. Frozen product is added through a screw from the feed hopper into the top of the drying chamber. A blower brings air through an electric heat exchanger into the chamber. Most of the air flows counter-currently relative to the feed through the chamber to the exhaust valve (1). The remaining air flows through the product stream, transporting the dried product to the collector (2). Temperature, humidity and air velocity are measured in each air stream. The interior of the dryer vessel is shown in Figure 2. Approximately 9,000 1.6 cm (5/8 in) diameter polyester balls are circulated through the vessel by means of a rotating screw. This fills the chamber. Other materials could be used. The balls enhance heat transfer to the food product. The balls are forced upward by the screw and move downward along the outer wall of the vessel, carrying product with them. A sieve separates the balls from the dried product. The dried product is then gravity fed to the collector.

Objectives

The objectives of this project include:

- To characterize the ball dryer through the use of material and energy balances.
- To improve and optimize the drying process for continuous operation.

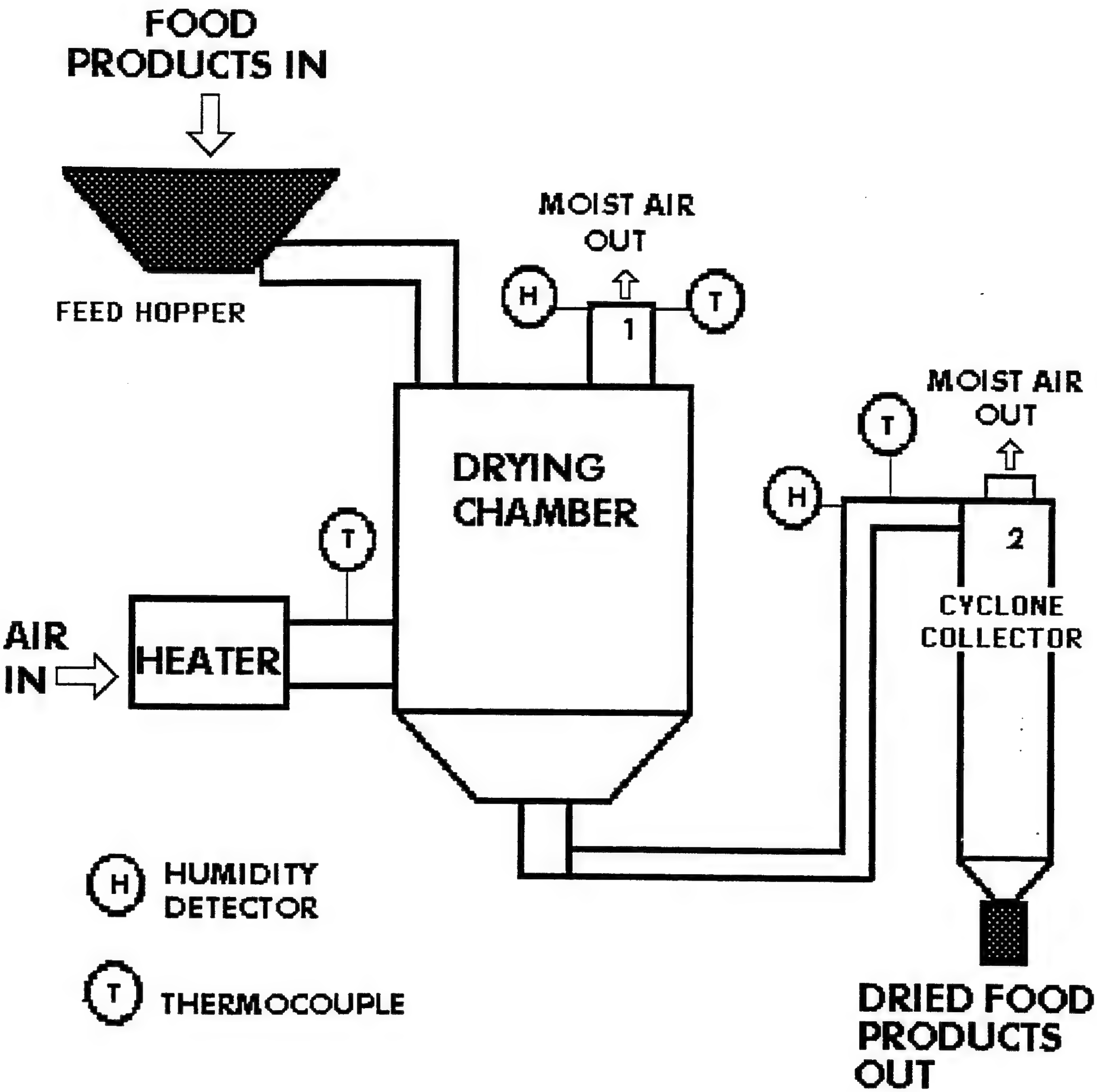

FIGURE 1 - SCHEMATIC DIAGRAM OF BALL DRYER SYSTEM

Drying Vessel

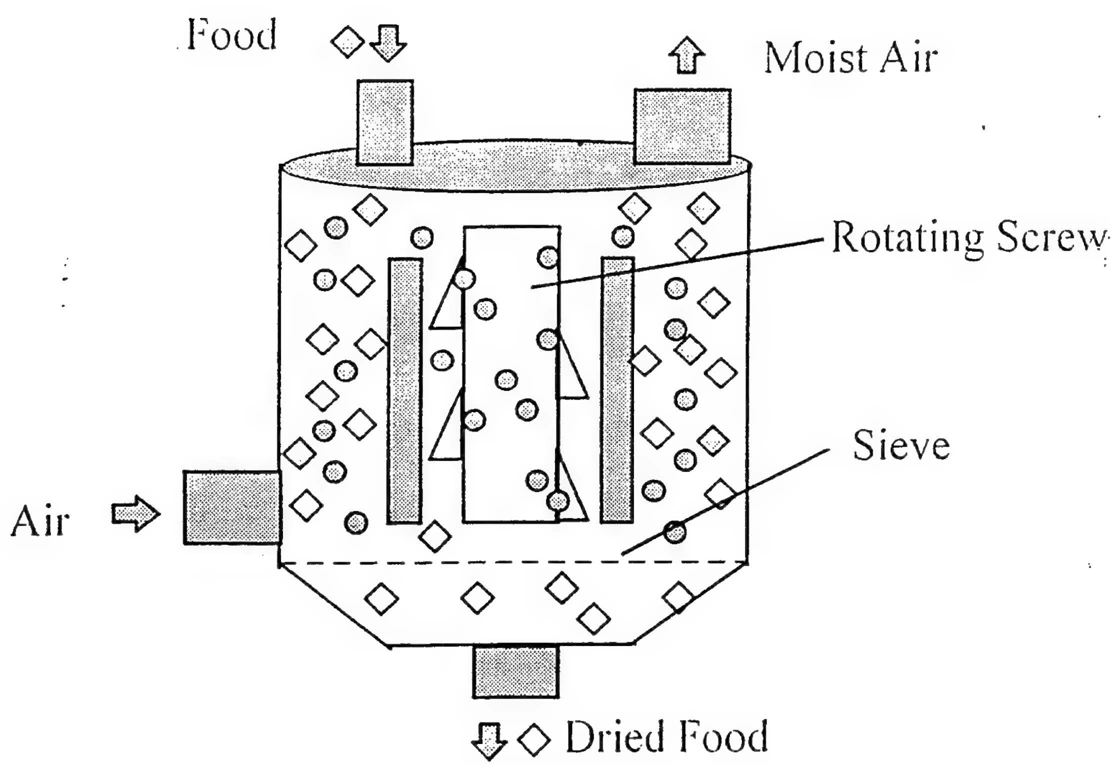

FIGURE 2 - INTERIOR OF BALL DRYER VESSEL

- To develop a predictive model for operating conditions based on characteristics of the food product.

Method of Approach

The first step in the investigation of the ball dryer operation was a general characterization of the system. In the initial test runs, the steady state levels for temperture, air-flow rate and humidity were measured at the inlets and outlets to develop mass and energy balances for the entire system. These measurements were used to quantify the drying capacity, heat losses and other process parameters. In addition to steady state operation, the start-up characteristics of the system were studied to determine the transient behavior of the equipment. Manipulation of independent variables in subsequent runs were studied to understand their effect on dryer operation. Manipulated variables during steady state include the inlet air temperature, the position of the two exhaust air valves, the ball screw rotation rate and the product feed rate.

For the characterization runs with product, an energy balance was performed for the system, as well as mass balances for air, water and solids, during the drying process. The frozen product was added to the system at a constant rate and the transient behavior of the system was monitored until a new steady state was achieved. At steady state, temperature, flow rate and humidity data were collected for each inlet and exit stream. In addition, a number of baseline experiments were conducted to determine the limits of operating conditions that would preclude operational difficulties.

Experiments were performed to determine the effect of operating parameters on the drying of frozen diced carrots. A statistical analysis of this data was used to test the significance of the control variables on the final water content and the quality of the product. Three measures of quality testing were examined: the rehydration ratio, the color of the rehydrated product and the percent moisture of the rehydrated product. These indices were compared to those of the control samples, which were both fresh and freeze-dried carrots. An optimal set of operating conditions for carrots was then developed and tested experimentally. Based on the measured drying rates and the physical properties of peas and potatoes, predictive models for these vegetables were developed. Finally, an economic analysis model was performed to determine the optimal usage of the ball dryer in conjunction with freeze-drying.

Experimental Design, Procedures and Modeling

Product Characterization

Initial Characterization

Three vegetables were investigated during this project: carrots, peas and potatoes. The carrots used were frozen, 0.95 cm (3/8 in) diced, Grade A Fancy, packed in 0.9 kg (2 lb) bags, with an initial moisture content of 89%. Frozen whole

peas, 0.5 cm (3/16 in) from 9 kg (20 lb) bulk packages, with 78% initial moisture, were used. They exhibited minor signs of freezer burn. The potatoes used were 1.27 x 0.95 x 0.16 cm (1/2 x 3/8 x 1/16 in) diced, Dehydrofrozen (Simplot™) with 51% initial moisture. The name and appearance of these potatoes indicated that they had been processed with some slight amount of drying. The rehydration and taste characteristics were consistent with raw, frozen potatoes. Carrots were chosen as a base product and were studied with the factorial design experiments, due to their resiliency and the absence of an outer shell. Peas are easily damaged by shear forces and were tested last to minimize excessive cleanup time. Texture analysis experiments were performed to quantify the mechanical strength of each vegetable product.

Drying Rate Studies

To further characterize the vegetables, drying rates of individual vegetable pieces were investigated in the laboratory. In the first experiment frozen diced carrots -- nearly thawed to simulate product entering the dryer -- were placed in the moisture analyzer at 79 C (175 F). The water content was recorded as a function of time. This data was converted to drying of grams of water per 100 grams of product, per minute. The experiment was repeated for potatoes and peas at various drying temperatures.

Ball Dryer Characteristics

Transient Behavior

The transient behavior of the system during start-up from ambient temperature was investigated. The temperature readings of each inlet and outlet stream, as well as the interior temperature, were monitored with time, until steady state operation was achieved. The transient trend for the start of the drying operation was also observed. Readings were taken from the time the frozen product was introduced into the system until a new steady-state was reached.

Material and Energy Balances

In order to perform mass and energy balances on the ball dryer, the inlet and outlet streams were charactrized in terms of temperature, air flow rate and water content. At the beginning of a drying run, the equipment was first brought from ambient to operating temperature. The ball screw motor was turned on full speed to accelerate heating of the vessel, which takes approximately 35 minutes. The temperature was set using the controller dial, which is calibrated in degrees Fahrenheit. The calibration of the thermocouple controller was confirmed using a hand-held thermocouple meter (Omega 871A, Digital Thermometer™). This meter was also used to confirm the calibration of gauge thermometers at each of the exit ports.

Air velocity measurements were made using a hot-wire anemometer (Kurz Instruments Model 441S™). These readings were taken at steady state drying

conditions to include the effects of temperature and pressure on volumetric flow rate calculated from the velocity multiplied by the cross-sectional area of the pipe. Temperature corrections were made based on the manufacturer's recommendation of +0.02% per degree Fahrenheit above 25 C (77 F). Calculation of the Reynolds number for each pipe confirmed that all flows were turbulent, so a constant velocity profile across the pipe was expected. Anemometer readings, with some fluctuations due to turbulence, confirmed that a constant velocity profile was established. An average of six measurements across the pipe diameter was used in the calculation of the volumetric flow rate. With the outlet ports, the presence of valves close to the exit ports required fitting an extension pipe of about six diameters length to allow smoothing of the velocity profile. These were made from rolled sheet metal and cardboard for the exhaust and product pipes, respectively.

The humidity of each stream was also measued. A digital wet-bulb thermometer (Heat Stress Monitor, Reuter-Stokes RSS214™) was used to obtain wet bulb measurements, which were combined with dry bulb measurements from the existing temperature gauges and converted to humidity using a psychometric chart. (Geankoplis, 1983) The inlet humidity was assumed to be that measured in the ambient air. The exhaust humidities were measured by placing the probe in a plastic bucket, which was then fitted over the exhaust to surround the probe in exhaust air. A plastic bag was used to cover the probe at the product port. It was observed that the high air velocity slightly decreased the wet bulb temperture reading due to increased evaporation. Several tests were conducted to determine the degree of bias reading and the humidity data was adjusted accordingly.

The air volumetric flow rates for each stream were calculated by multiplying the average air velocity by the corresponding inlet and outlet cross-sectional area. Using the ideal gas law and the absolute humidity, the mass flow rate of dry air was obtained from equation 1. (Geankopolis, 1983)

$$V_m = V_H \left[(22.41/273)\,(T)\,(H)\,(1/28.97 + 1/18.02)\right]^{-1} \qquad (1)$$

Where: V_m = mass flow rate of dried air (kg air/min)

V_H = air volumetric flow rate for individual stream (ft^3 air/min)

T = Temperature (^oF)

H = Absolute Humidity (%)

The humid air heat capacity is a weak function of temperature over the temperature range of the drying system and is related to the humidity by equation 2. (Geankoplis, 1983).

$$C_s = 1.005 + 1.88\,H \qquad (2)$$

Where: C_s = humid air heat capacity (kJ/kg dry air ^oK)

Feed Rate and Residence Time

After the ball dryer achieved steady state, as determined by the leveling of the temperature readings, the screw was activated to feed frozen product from the hopper. The feed rate was calibrated by weighing the amount of product dispensed per minute, for various controller settings. The hopper was maintained at least 1/3 filled with product to eliminate backdraft from the feed port. Frozen product was taken from the -29 C (-20 F) freezer only when needed, to avoid early thawing. Dried product samples were collected every 30 minutes. After the system had achieved steady state, the necessary samples were collected and the operating parameters reset. For some runs with high final moistures (above 35%), the exhaust valve was briefly closed once or twice during the run, to flush any heavy pieces out of the product tube.

Statistical Design Experiments

Process Limitations

Several initial ball dryer experiments were performed to identify the practical limitations on the range of operating conditions. A minimum practical inlet temperature of 88 C (190 F) has been chosen to ensure sufficient drying. Although 127 C (260 F) is available, on humid days the maximum attainable temperature is 110 C (230 F). As the ambient humidity increases, the heat capacity of the inlet air increases, thus decreasing the maximum temperature attainable for the fixed heating rate.

The ball screw speed meter was calibrated to determine the corresponding rotational speed in units of revolutions per minute (RPM). The screw speed ranged from 1.2 to 12.0 RPM. Two experiments were conducted to determine the effect of screw speed and feed flowrate on carrot drying. For both experiments, the inlet air temperature was set at 104 C (220 F) and the exhaust valve at 50% open.

In the first run the screw speed was set at 5.4 RPM and the carrot feed rate at 0.25 kg (0.55 lb) per hour. This experiment was terminated after 50 minutes because no product was collected. The bottom of the drying vessel was opened and found to contain about 2.3 kg (5 lb) of wet carrots. The moisture content of the carrots was 75%.

The second experiment was performed at a feed flow rate of 0.16 kg (0.35 lb) per hour and a screw speed of 2.4 RPM. As in the previous experiment, the majority of the product was stuck to the bottom of the drying vessel. The final moisture content of these carrots was 37%.

The large difference in the final moisture content between these two experiments and the base case led to an investigation of the effect of screw rotational speed on residence time. Experiments were performed by initially placing

25 g (0.06 lb) of dry carrots (10% moisture content) on top of the rotating screw cylinder where the frozen products typically fall down from the feed pipe. The ball screw was turned on and the amount of product collected was monitored over time. The average residence time was obtained when approximately half of the product was collected. This experiment was repeated with other rotational speeds. The results are shown in Figure 3. The residence time declined quickly between 1.2 and 3.6 RPM before leveling off. The ball screw speed was fixed at 1.2 RPM for all further experiments as a result. A greater residence time would result in increased drying.

The residence time of frozen carrots (89% initial moisture content) was compared with the dry carrot result. This was done by placing 40 pieces of frozen diced carrots on top of the inner cylinder prior to starting the ball screw. Because the product air velocity was insufficient to transport the frozen carrots to the cyclone collector, the bottom of the vessel was left open to allow the pieces to be collected as they fell. The ball screw speed was set at 1.2 RPM and the average residence time was determined when 20 pieces of carrot were collected. The residence time increased from 50 to 80 minutes with as the moisture content changed from 10 to 89% between the dry and wet carrots respectively .

The maximum estimated range for the product feed rate was 500 g (1.1 lb) per min, but clogging in the feed tube was observed at higher speed, thus limiting the maximum rate to 96 g (0.44 lb) per min. A minimum value of 38 g (0.084 lb) per min was set since this had been proven to yield a favorable product at a reasonable throughput. The product stream velocities had to be great enough to transport dried product to the collector. The velocity limitation was not a problem as long as products were sufficiently dried so as not to limit the position of the main exhaust valve. However, the lack of a tight seal eliminates total closure of the valve. Thus, 25% was chosen as a minimum opening and 100% as the maximum.

High moisture products are often sticky and bond to the inside of the product feed line. This may account for some observed accumulation of product in the exit line. This effect was minimized by using lecithin aerosol spray (Pam™) to lubricate the interior of the vessel. Table 1 gives a summary of the total available operating range for each variable as compared to the narrow range which were studied in subsequent experiments.

Table 1 - Total Ranges and Practical Operating Ranges for Ball Dryer Variables

Variable	Full Range	Experimental Range
Inlet Air Temperature	Ambient - 127 C (260 F)	90 - 110 C (195 - 230 F)
Product Feed Rate	0 - 0.5 kg (1.1 lb) per min	0.038 - 0.096 kg per min (0.084 to 0.21 lb) per min)
Exhaust Valve Setting	0 - 100 % open	25 - 100% open
Ball Screw Speed	1.2 - 16 RPM	1.2 RPM

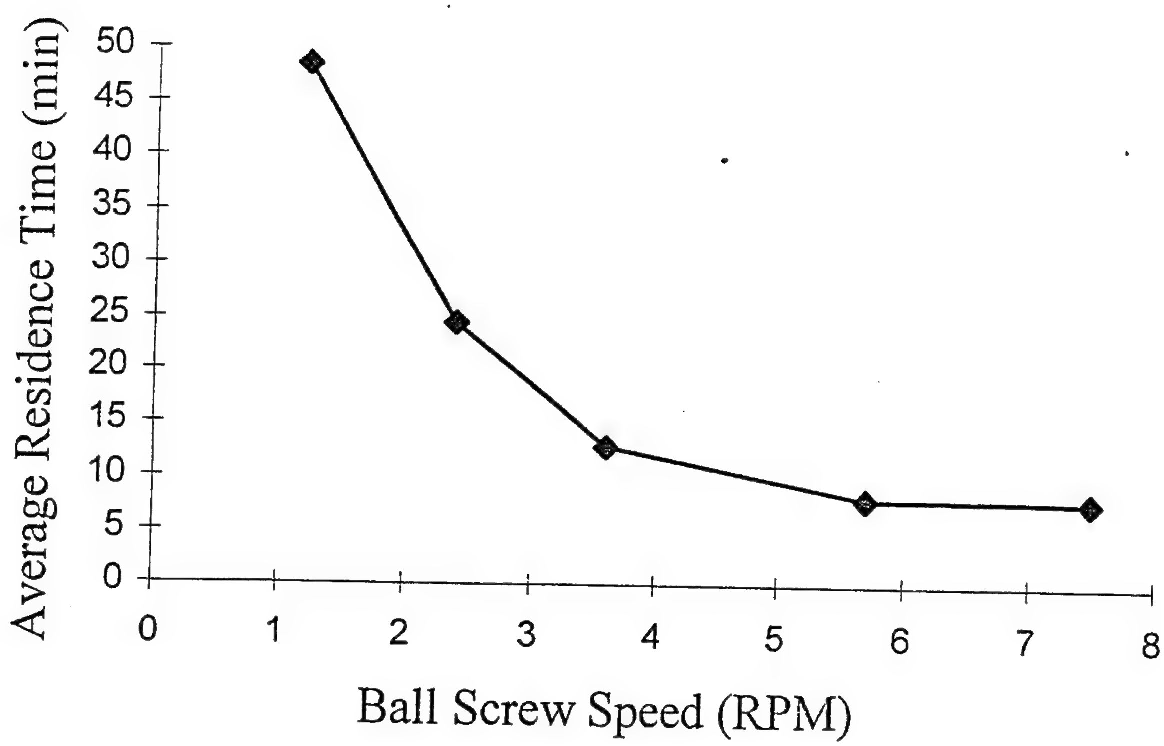

FIGURE 3 - SCREW SPEED AND RESIDENCE TIME

Factorial Design for Experiments

A set of designed experiments was developed to find the optimum drying conditions after the practical limits for continuous operation were determined. A factorial design was chosen with three operating factors at two levels each for eight runs. An additional run at the midpoint of the expermintal range of variable levels was made to permit analysis on nonlinear interactions. The three factors used were inlet air temperature (T), feed rate (F) and exhaust valve position (O). The series of experiments that were performed are shown in Table 2.

Table 2 - Experimental Design

Experiment Number	Inlet Air Temp. ^{o}C (^{o}F)	Feed Rate g/min (lb/min)	Exhaust Valve % open
1	110 (230)	96 (0.21)	100
2	110 (230)	96 (0.21)	25
3	110 (230)	38 (0.08)	100
4	110 (230)	38 (0.08)	25
5	91 (195)	96 (0.21)	100
6	91 (195)	96 (0.21)	25
7	91 (195)	38 (0.08)	100
8	91 (195)	38 (0.08	25
9	101 (213)	67 (0.15)	50

Characterization

Three analytical methods were used to characterize the dried vegetable products: moisture analysis, rehydration and colorimetry. The percent water content of the dried sample was the primary measure of drying effectiveness. This was measured using a moisture analyzer which heats the sample at a constant temperature to drive off free water. The analyzer weighs the sample before and after heating to determine the percent moisture of the whole sample.

Another measure of product quality was rehydration in boiling water to simulate cooking of the product. The standard procedure was to expose a measured mass of dried sample to boiling water for two minutes, then drain off the water and weigh the rehydrated material. The rehydration ratio was defined as the mass of water absorbed by the dried sample divided by the mass of the dried sample. In addition, the percent water was measured for each rehydrated sample in the Computrac™ moisture analyzer.

The appearance of the rehydrated food was quantified using colorimetry. A Hunter™ computerized spectrophotometer was used to measure color parameters for each rehydrated sample. These were compared to two control samples: Pre-frozen, thawed carrots boiled for two minutes (Control 1) and freeze-dried carrots boiled for two minutes (Control 2). The spectrophotometric scale used for

color description was based on the "L", "a" and "b" opposing color scales developed by the International Committee on Illumination (CIE) (Peleg, J. and Bagley, M., 1983). The "L" dimension defines the lightness. The "a" dimension refers to the red-green hues. The "b" dimension refers to the blue-yellow hues. The three dimensions uniquely locate the sample on color and intensity coordinates to quantify sensory perceptions such as "darker" or "yellowish". The color of the dried samples were compared to the control samples to quantify changes affected by the ball dryer.

Modeling

Carrots

An empirical relationship was developed to predict the percent water removed in carrots, as well as product quality, as a function of the operating parameters. This model is capable of estimating the effect of all control variable combinations on the responses. In this study, the three main effects (T, F, O) and the three two-way interactions (TxF, TxO, OxF) effects were studied. The basic model is described by equation 3.

$$y_k = \beta_o + \sum \beta_i x_i + \sum \beta_{ij} x_i x_j \qquad (3)$$

where y_k = dry product characteristics and total moisture removal rate (kg per hr)

β_i = characterizing values for each controlling variable

x_i = controlling variables (T, F and O or $O^{0.5}$)

The dry carrot charactristics include the percent water removed[1], the difference in color and the % moisture of the rehydrated product relative to the control sample.

The responses in the model were correlated with the exhaust valve position and the square root of the position. The proposed 0.5 power effect is supported by the correlation of Nusselt number (Nu) and Sherwood number (Sh) with Reynolds number (Re). For a sphere in a gas system with Re between 350,000 and 760,000, the correlation between the two dimensionless groups is described by equation 4.

$$Nu = 2 + (0.4\ Re^{0.5} + 0.06\ Re^{0.67})\ Pr^{0.4}\ (\mu/\mu_s)^{0.25} \qquad (4)$$

μ = viscosity, poise

This correlation is for the heat transfer coefficient; an analogous correlation exists for the Sherwood number to describe mass transfer. Because the estimated Re

1. This is defined as the difference between the initial and final water contents divided by the initial water content.

for the falling food products in the ball dryer is 312 and air velocity is directly related to the valve position the drying rate is expected to vary with the valve position to the 0.5 power.

A t-test was performed on all parameters to determine the significance of their effects on the response. Coefficients with a relatively low t-value resulted in rejection of the associated parameters from the model. The predictabilty of the model was tested by comparison with two additional experiments.

Potatoes, Peas and Other Vegetables

The model was modified for other vegetable products by multiplying the coefficients of the carrot model with the ratio of the vegetable drying rate by the carrot drying rate (k_{VC}). The drying rate as a function of water content can be experimentally determined by using the moisture analyzer. The functional form of the modified model is defined by Equation 5:

$$y_i = k_{VC} [\beta_0 + \Sigma\beta_i x_i + \Sigma\beta_{ij} x_i x_j] \qquad (5)$$

Where k_{VC} equals the ratio of the new vegetable drying rate and the carrot drying rate. The modified model was determined and tested for peas and potatoes.

Results

Product Drying Rate Studies

The drying rate for carrots as measured using the moisture analyzers is presented in Figure 4. The standard error, based on three runs, was less than 10 percent. All subsequent drying rate measurements followed the same trend and were not repeated.

After characterizing the carrot drying rate, further experiments were performed with peas and diced potatoes. These results are compared with those for carrots in Figure 5. Note that the drying rate is plotted against the percent of free water remaining in the sample rather than the absolute water content. This is done to normalize the results for the differences in initial water content among the three vegetables: 89% for carrots, 78% for peas and 51% for potatoes.

The drying rate ratio, k_{VC}, for relative drying of peas and potatoes to carrots was also determined. The inverse of k_{VC} is the scaling factor required to match the drying rate of peas and potatoes to carrots. The scaling factors are 1.3 and 1.6, which corresponds to the drying ratios of 0.77 and 0.63 for peas and potatoes, respectively, are shown in Figure 6.

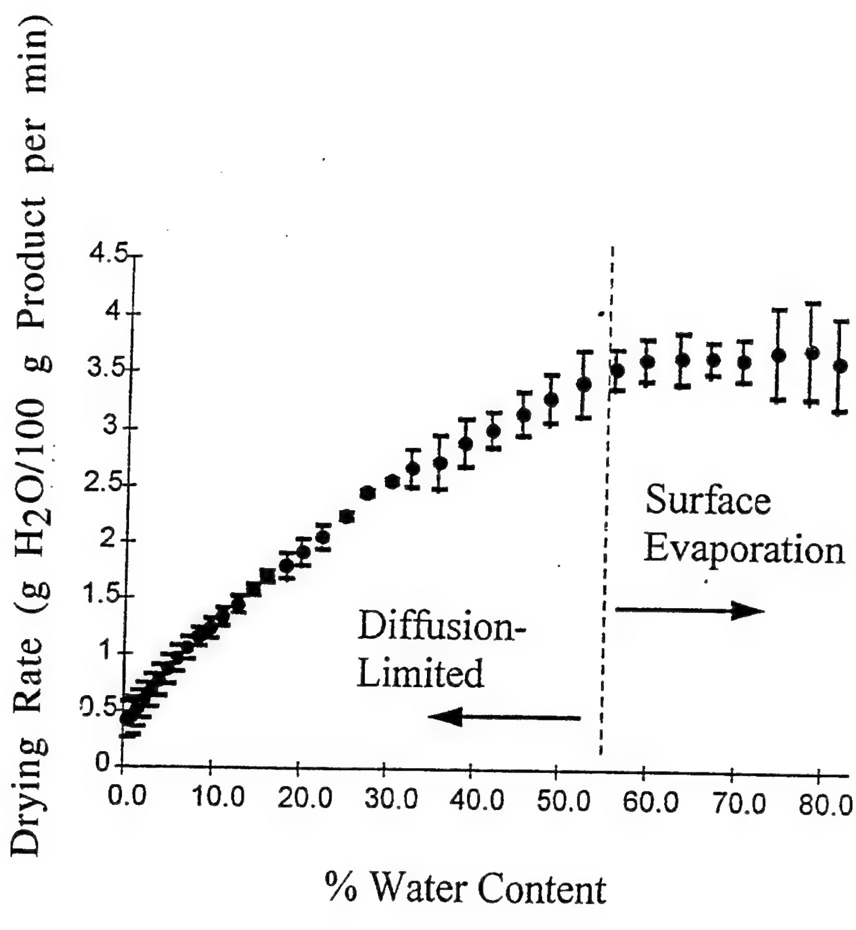

FIGURE 4- CARROT DRYING RATE

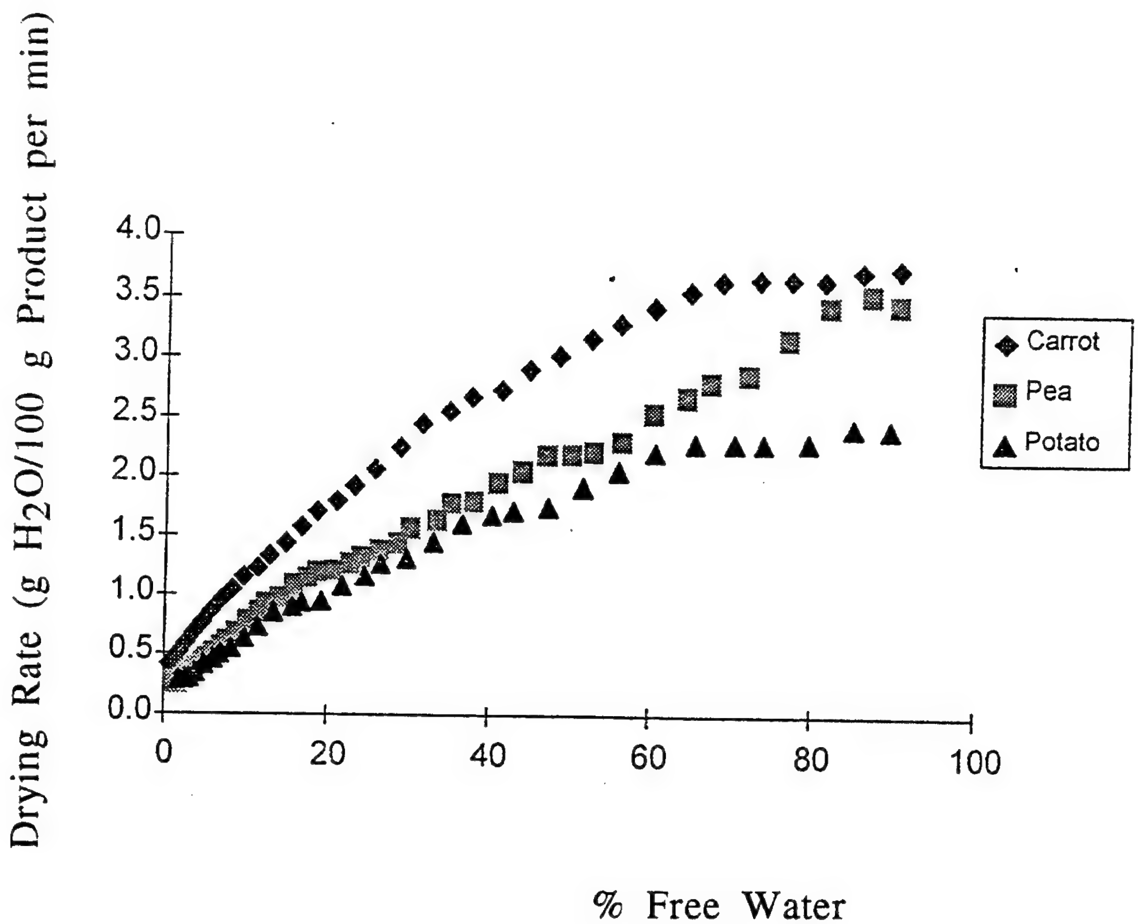

FIGURE 5 - DRYING RATE COMPARISON

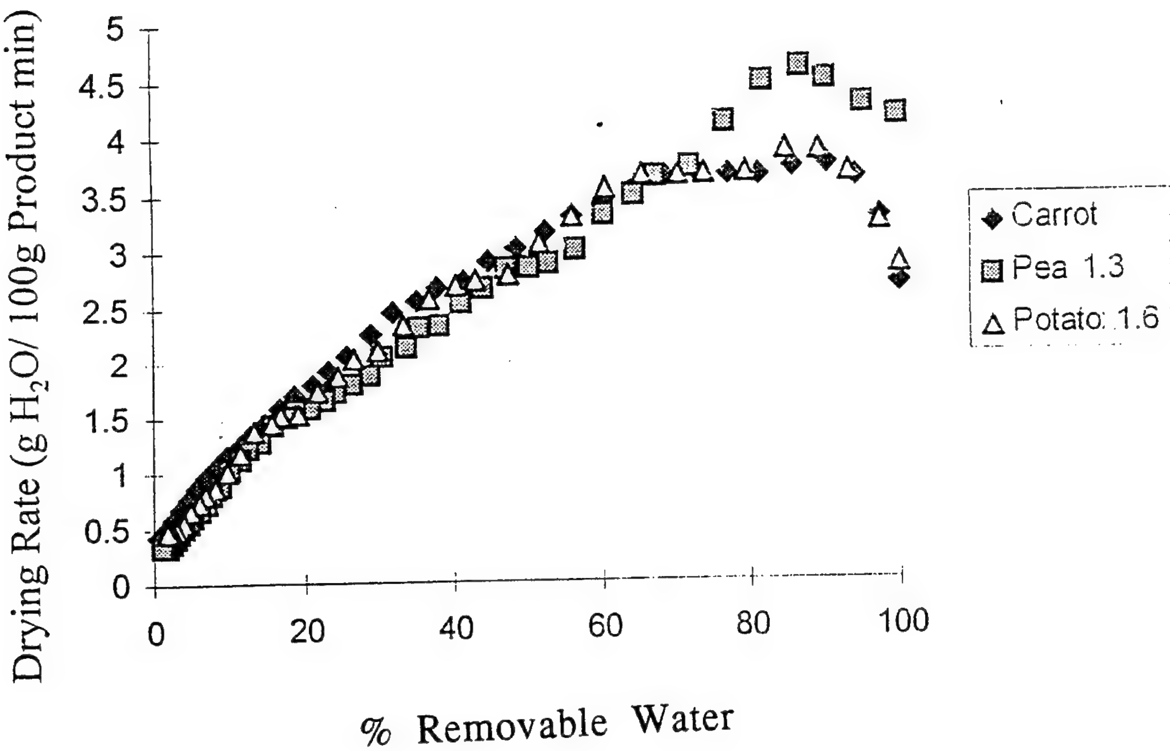

FIGURE 6 - DRYING RATE RATIO (k)

Ball Dryer Characterization

Transient Behavior

Initial ball-dryer experiments were used to observe the transient behavior of the system, as well as to establish base operating parameters as a reference for subsequent runs. The conditions chosen were based on those used in a previous M.I.T. Practice School Project (Langner, M. et al, 1995). The inlet air temperature was set at 220 F (104 C), the feed rate was 100 g (0.22 lb) per min of frozen diced carrots, and the ball screw speed was set to its minimum value of 1.2 RPM. Measurements were taken at five minute intervals to establish the transient behavior of the dryer system.

Figure 7 shows temperature plots for the air inlet, exhaust and product outlets and the vessel interior (bottom) as the system is heated from room temperature. Temperatures for the inlet and interior reach equilibrium after 40 minutes, while the exhaust ports require an additional 20 minutes to come to operating temperature. Since this feed rate is high, the transient behavior of the following experiments was shortened.

When the empty dryer reached steady-state, frozen product was fed continuously until dried product was obtained in the product stream. Temperature plots for the transition from the empty steady-state to the continuous operation steady-state are shown in Figure 8. The time required for the transition was about 35 minutes; the largest temperature change was observed for the exhaust outlet, which dropped 15 C (27 F) after addition of frozen product.

The moisture content of dried product samples was determined once steady - state conditions were achieved. The feed hopper was kept full throughout the run and, as a result, no backdraft airflow was observed. The inlet volumetric air flow rate, based on measured air velocity, was in agreement with the motor specifications, which uses the static pressure data measured at the feed stream.

Ball Dryer Mass and Energy Balances

Mass and energy balances were performed on the empty ball dryer to estimate the mass and energy losses. The inlet temperature was set at 104 C (220 F) with the exhaust valve 25% open. All temperature readings were obtained from the thermometers that were mounted to each stream (Figure 1). The results for the air velocity corrected to normal temperature and pressure (NTP), are presented in Table 3.

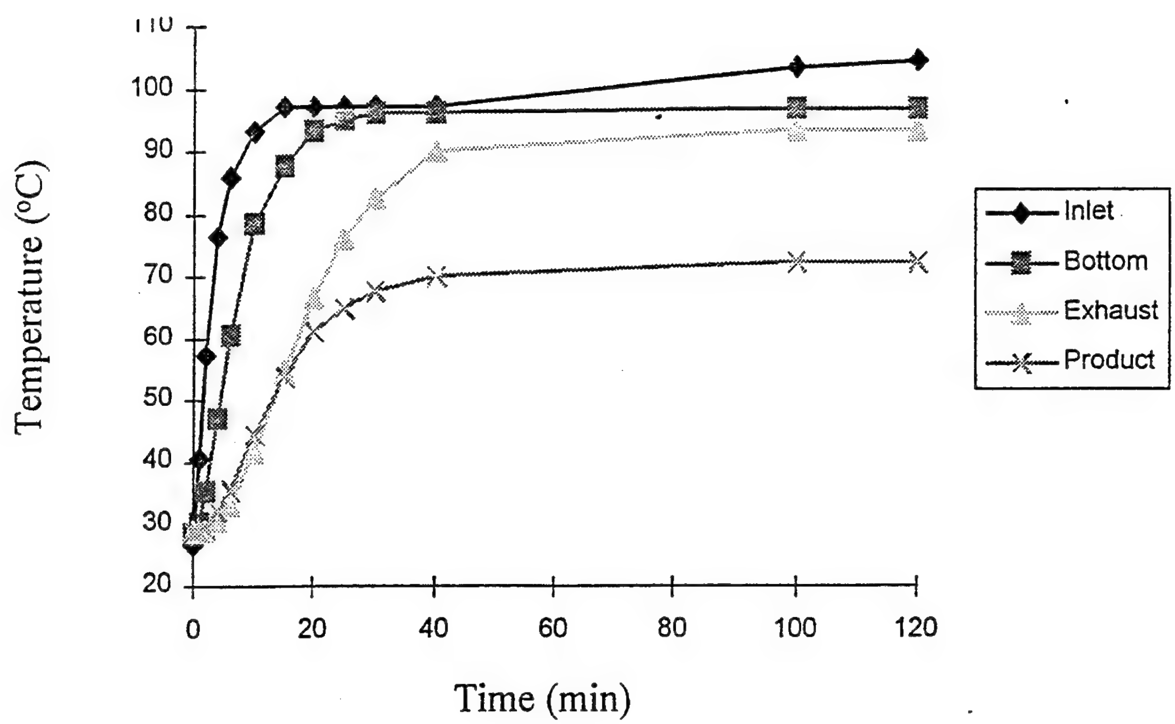

FIGURE 7 - TRANSIENT TEMPERATURE PROFILES (START-UP)

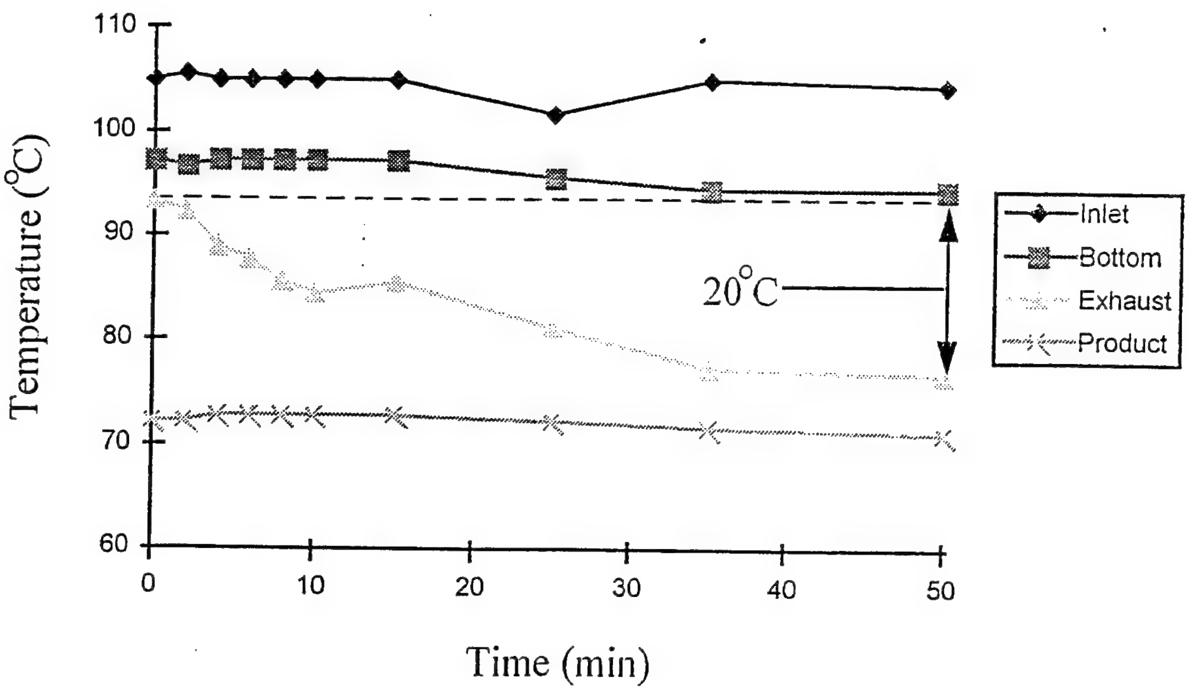

FIGURE 8 - TRANSIENT TEMPERATURE: PROFILE RESPONSES TO PRODUCT ADDITION

Table 3 - Air Velocity Measurements

		Air Velocity				
Exhaust Valve % Open		0	25	50	75	100
Exhaust Outlet	(m/min)	333 ± 29	381 ± 23	391 ± 32	401 ± 23	401 ± 23
	(ft/min	1091 ± 95	1250 ± 76	1283 ± 104	1316 ± 76	1316 ± 76
Product Outlet	(m/min)	216 ± 27	99 ± 19	91 ± 8	73 ± 16	81 ± 4
	(ft/min)	708 ± 88	325 ± 63	300 ± 25	241 ± 52	266 ± 14
Product Line	(m/min)	1646	1280	975	853	853
	(ft/min)	5400	4200	3200	2800	2800

The mass flow rates of water and air were calculated as well as the enthalpy (25 C reference state) associated with each flow. By subtracting the values of the two outlets from the inlet stream, the percent loss can be calculated. The mass and energy balances results for the empty system are summarized in Table 4

Table 4 - Mass and Energy Balances for Empty Ball Dryer

Measurement	Inlet	Exhaust Outlet	Product Outlet	In-Out	% Loss
Temperature (C)	104.4	90.0	68.9	--	--
(F)	220	194	156	--	--
Humidity (mass H_2O/mass dry air)	0.013	0.017	0.010	--	--
Volumetric Flow (m^3/min)	8.18	5.97	0.88	--	--
(ft^3/min)	289	210	31		
Dry Air Flow Rate (kg/min)	7.49	5.71	0.90	0.88	12
(lb/min)	16.5	12.6	1.98	19.4	12
Water Flow Rate (kg/min)	0.10	0.07	0.01	0.03	19
(lb/min)	0.22	0.15	0.02	0.07	19
Total Mass Flow Rate (kg/min)	7.59	5.76	0.91	0.91	12
(lb/min)	16.7	12.7	2.0	2.0	12
Enthalpy Flow Rate (kJ/min)	612.7	380.4	40.3	192.2	31
(BTU/min)	581	361	38	182	31
Energy Flow (kJ/hr) (kW)	10.2	6.3	0.7	3.2	31

These values were obtained with a sealed feed inlet to simulate a filled feed hopper. The drying capacity of the ball dryer was estimated based on the energy required to bring ice from 0 C (32 F) to water vapor at 85 C (185 F). The maximum heating capacity was calculated by using the difference between the air inlet

temperature and 35 C (95 F) 10 C (18 F) above ambient temperature) as the maximum temperatue drop. The calculated maximum drying capacity of the ball dryer is 6.8 kg (15.0 lb) moisture per hour. Note that some error is introduced by humidity measurements, which result in differences betwen the mass balances for air and water.

The mass and energy balances were also performed on the ball dryer during steady state operation. The food product was frozen carrots at - 13 C (- 9 F) with 90% water content. The feed controller was set at 15% which provided a 38 g (0.08 lb) per min feeding rate for feed calibration. The inlet temperature, the ball screw rotational speed, and the exhaust valve were set at 114 C (238 F), 1.2 RPM and 25% open respectively. Three criteria were used to determine whether steady-state operation had been achieved: constant exit air temperatures, constant product moisture content and equal dry product flows through the feed and product lines. In the mass and energy balance calculations, no product accumulation was assumed. The summarized results are shown in Table 5.

Table 5 - Mass and Energy Balance for the Steady State Ball Dryer

Measurement		Inlet	Feed	Exhaust Outlet	Product Outlet	Product Collector	In-Out	% Loss
Temperature	(C)	114.4	-13.0	82.8	77.8	77.8	--	--
	(F)	240	8.6	181	172	172	--	--
Humidity (mass H_2O/dry air)		0.012	--	0.016	0.012	--	--	--
Vol. Flow	(m^3/min)	8.18	--	5.97	0.88	--	--	--
	(ft^3/min)	289	--	210	31	--	--	--
Prod. Flow	(kg/min)	0.0	0.004	0.0	0.0	0.04	0.0	0
	(lb/min)	0.0	0.009	0.0	0.0	0.09	0.0	0
Dry Air Flow	(kg/min)	7.31	--	5.77	0.87	--	0.82	9
	(lb/min)	16.08	--	12.69	1.91	--	1.80	9
H_2O Flow	(kg/min)	0.09	0.034	0.09	0.01	0.04	0.02	12
	(lb/min)	0.20	0.074	0.20	0.02	0.09	0.04	12
Total Mass Flow	(kg/min)	7.36	0.038	5.87	0.87	0.03	0.83	9
	(lb/min)	16.19	0.084	12.91	1.91	0.07	1.83	9
Enthalpy Flow	(kJ/min)	671.9	-16.3	422.5	47.5	5.39	189.8	27
	(BTU/min)	637	-15.5	401	45.0	5.11	180	27
Energy Flow	(kJ/hr) (kW)	11.2	-0.27	7.04	0.8	0.1	3.16	27

Air Flow Rate

Each of the two air outlets in the ball dryer system is fitted with a valve. The exhaust valve has a stronger effect on the distribution of air between the exhaust and product lines since the mass flow rate for the exhaust outlet is approximately six times the product outlet. Thus, the product valve setting remained constant for this study. By opening the exhaust valve, the amount of air available to bring dried product to the collector is decreased (see Table 3). The velocity of this air must be sufficient to entrain the product particles. A simple experiment was performed to confirm that dried product at 13% moisture is transported by the product stream at each extreme of the exhaust valve setting, so this is not an issue for dried carrots. Table 4 shows the results of opening the exhaust valve on product pipe airflow.

The exhaust valve setting has a strong effect on the volumetric flow and temperature of the inlet air stream. Since the inlet air fan is driven by a constant velocity motor, the volumetric flow provided is inversely proportional to the static pressure at the fan outlet. Closing the exhaust valve increases the inlet pressure, causing a lower airflow into the dryer. When running the heater at its highest temperature, the heating rate is at its maximum value. The air is heated according to Equation 6.

$$Q = m\, c_p\, \Delta T \qquad (6)$$

Where Q = heating rate

m = mass flow rate of air

C_p = heat capacity of the gas

ΔT = temperature increase

For a constant Q at maximum heating, an increase in m causes a corresponding decrease in the temperature difference. This analysis agrees with the observation that opening the exhaust valve decreases the maximum air inlet temperature.

Feed Rate

Product damage caused by the feed system has been a major cause for underutilization of the ball dryer. Specifically, mechanical damage to the product has occurred in the screw feeder, making the final dried product unsuitable for use. Three major causes of feed problems have been addressed during the project. The first is the backdraft of hot air into the feed hopper due to the positive pressure in the drying vessel, causing partial thawing of frozen products. The thawed material is more susceptible to shearing between the screw and the neck of the feed hopper. A simple solution to this problem was found by keeping the hopper filled with frozen product at all times, effectively blocking the passage of air from the dryer. Since the dryer is being considered for continuous operation, the hopper will be filled to maintain a constant feed, thus avoiding the backdraft issue.

A second effect involves the mechanical shearing of softer food products in the space between the screw and the feed hopper neck. Any particles caught in the space, especially softer foods like peas, may be severely sheared and form a paste which subs equently blocks the feed neck. A design modification is being implemented using an insert which snugly fits around the screw, providing no spaces for food particles to get caught and sheared.

A final feed-related problem is due to the speed at which the screw is driven. For speeds above 125 g (0.28 lb) per min (30% of total speed), the food product begins to accumulate in the feed neck. Incoming product compressed existing product, causing further mechanical damage and blockage of the inlet. This effect was observed for each of the three types of vegetable product. Based on this observation, 96 g (0.21 lb) per min was set as a practical upper limit for the product feed rate in further experiments.

Statistical Design Experiments

The results for carrot experiments are presented in Table 6. The average initial moisture content was 89.8 $\pm$ 1.6%. Experiments 1 - 9 are the designed experiments that were used to develop the drying model. Additional test runs were performed to evaluate the model predictive performance. The applicability of extending the predictive model to other foodstuffs was assessed using the data obtained from the pea and potato experiments shown in Tables 7 and 8. In Tables 6 through 8, Control 1 and Control 2 are the characteristics of frozen and freeze-dried products respectively.

Table 6 - Carrot Experimental Results

	Temp. In		Feed		Valve	Final
Experiment	C	F	g/min	lb/min	% Open	% Moisture
Control 1	NA	NA	NA	NA	NA	NA
Control 2	NA	NA	NA	NA	NA	7.1
1	110	230	96	0.21	100	30.3
2	110	230	96	0.21	25	36.6
3	110	230	38	0.08	100	13.6
4	110	230	38	0.08	25	15.0
5	91	195	96	0.21	100	34.2
6	91	195	96	0.21	25	47.1
7	91	195	38	0.08	100	25.3
8	91	195	38	0.08	25	28.8
9	101	238	67	0.15	50	21.8
Test 1	99	210	38	0.08	25	24.8
Test 2	110	230	158	0.35	25	50.5
Test 3	114	238	38	0.08	50	9.9

Table 6 (Continued)

Experiment	Drying Rate kg/hr	lb/hr	Rehydration Ratio	Color L	a	b
Control 1	NA	NA	NA	44.7	37.9	51.0
Control 2	NA	NA	5.87	45.6	38.7	50.0
1	3.4	0.007	1.27	44.0	36.0	46.2
2	3.1	0.007	1.22	42.4	34.9	43,6
3	1.7	0.004	1.74	42.7	31.3	47.1
4	1.7	0.004	1.52	42.2	32.9	46.3
5	3.2	0.007	1.30	42.9	36.0	43.7
6	2.5	0.006	1.13	43.9	36.5	45.8
7	1.5	0.003	1.43	45.2	34.8	50.9
8	1.4	0.003	1.48	44.9	34.7	48.7
9	2.7	0.006	1.45	44.2	42.8	46.3
Test 1	1.5	0.003	1.47	46.0	34.9	48.5
Test 2	3.7	0.008	0.94	45.2	34.0	51.3
Test 3	1.8	0.004	1.64	37.8	25.7	40.2

Table 7 - Pea Experimental Results

Experiment	Temp. In C	F	Feed g/min	lb/min	Valve % Open	Final % Moisture
Control 1	NA	NA	NA	NA	NA	NA
Control 2	NA	NA	NA	NA	NA	0.51
Test 1	102	215	35	0.08	100	21.8
Test 2	102	215	65	0.14	25	20.2

Table 7 (Continued)

Experiment	Drying Rate kg/hr	lb/hr	Rehydration Ratio	Color L	a	b
Control 1	NA	NA	NA	41.0	-10.0	33.9
Control 2	NA	NA	2.16	40.1	-11.5	31.3
Test 1	0.96	2.1	1.11	37.0	-7.1	30.1
Test 2	2.29	5.0	1.21	38.0	-9.2	30.1

Table 8 - Potato Experimental Results

Experiment	Temp. In C	F	Feed g/min	lb/min	Valve % Open	Final % Moisture
Control 1	NA	NA	NA	NA	NA	NA
Control 2	NA	NA	NA	NA	NA	0.40
Test 1	113	235	35	0.08	100	21.8
Test 2	102	215	40	0.09	25	25.8

Table 8 (Continued)

	Drying Rate			Color		
Experiment	kg/hr	lb/hr	Rehydration Ratio	L	a	b
Control 1	NA	NA	NA	67.0	-2.1	15.9
Control 2	NA	NA	0.51			
Test 1	0.62	1.4	0.49	55.1	5.4	20.9
Test 2	0.61	1.4	0.53	59.7	5.1	20.8

Modeling

Carrots

A regression analysis with % water removed (%WR) as the response showed that the nonlinear interactions were not statistically significant. The model with the valve position to the 0.5 power also showed a slightly better correlation coefficient, R, than a linear model. The final model is described in Equation 7 and the coefficients with their significance in Table 9. A variable is more important as its P-value approaches 0.0.

$$\%\,WR = \beta_o + \beta_1 T + \beta_2 F + \beta_3 O^{0.5} \qquad (7)$$

$$R = +0.927$$

Table 9 - Carrot Drying Model

Factor	Coefficient, β_1	Standard Error	P-value
Intercept	+ 0.1748	0.2422	0.5028
Inlet Temperature (F)	+ 0.0030	0.0011	0.0418
Feed Rate (kg/hr)	- 0.0030	0.0007	0.0059
$(\%\ \text{open})^{0.5}$	+ 0.0111	0.0076	0.2034

According to the P-value of the three coefficients in the carrot model, the feed rate is the most significant controlling variable, followed closely by the inlet temperature. However, the effect of the valve position on the percent water removed is not significant. This was expected since the air velocity varies from 280 m (1250 ft) per minute at 25% open to 400 m (1310 ft) per minute at 10% open. This is only a 5% change, explaining the negligible impact of valve position to the drying process.

The predictability of the model was tested with two additional trials. The model predicts the measured drying rate to within 2% difference as summarized in Table 10. One notes that Test 2 was significantly ouside of the variable range for which the model was developed.

Table 10 - Carrot Drying Model vs. Experimental Results

Test	Temp. C	Temp. F	Feed/min g	Feed/min lb	Valve (% Open)$^{0.5}$	% WR Exp.	% WR Model	% Difference
1	99	210	38	0.083	5	0.72	0.74	+ 1.66
2	110	230	158	0.35	5	0.4	0.43	- 0.63

Another model of the form of Equation 7 was developed to predict the total drying rate (feed rate) (% water removed). The effect of the control variables on the total drying rate was determined and the statistical analysis of the data is sumarized in Table 11.

Table 11 - Carrot Total Drying Rate Model

Factor	Coefficient, β_1	Standard Error	P-value
Intercep	- 1.8201	1.2371	0.2012
Inlet Temperature (F)	+ 0.0097	0.0055	0.1415
Feed Rate (kg/hr)	+ 0.0255	0.0033	0.0006
(% open)$^{0.5}$	+ 0.0540	0.0387	0.2221

The feed rate has a significant positive effect on the total rate of drying. In fact, a relatively linear correlation can be found between total drying and the feed rate as depicted in Figure 9. The inlet temperature and the valve position are not statistically significant based on a 90% confidence level. The model's predictive ability for the two test trials is summarized in Table 12.

Table 12 - Carrot Total Drying Rate Model vs. Experimental Results

Test	Temp C	Temp F	Feed/min g	Feed/min lb	Valve % open$^{0.5}$	Exp. H_2O per hr. kg	Exp. H_2O per hr. lb	Model	% Diff.
1	99	210	38	0.08	5	1.8	4.0	1.45	-2.15
2	110	230	158	0.35	5	3.72	8.2	4.70	+26.27

A single variable linear regression was also tested where the total drying rate is a function only of feed rate. The results are similar to the value obtained from the multiple variable model where the predictive value for the Test 2 condition is 26% higher than the experimental value.

Although the inlet temperature was not statistically significant at the 90% confidence level in the total drying rate model, it still provided some notable effects as shown in Figure 10 . The two sets of data represent the effect of inlet temperature on the total drying rate at two different feed rates. The slopes of the lines suggest that the total drying rate would increase by approximately 15 g (0.033 lb) moisture

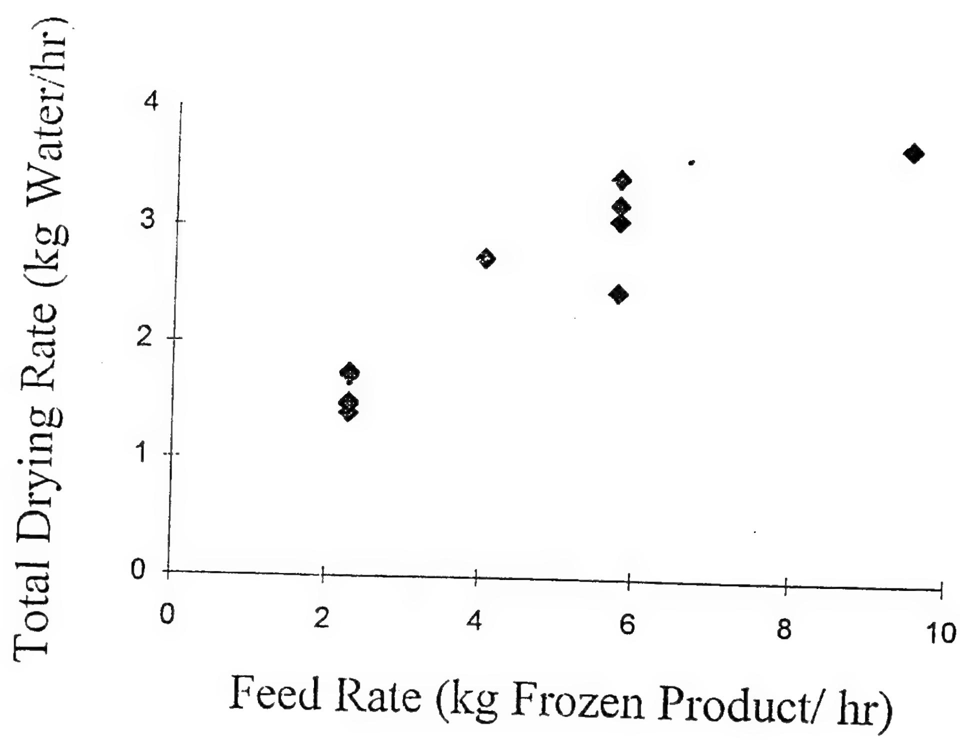

FIGURE 9 - FEED VS. TOTAL DRYING

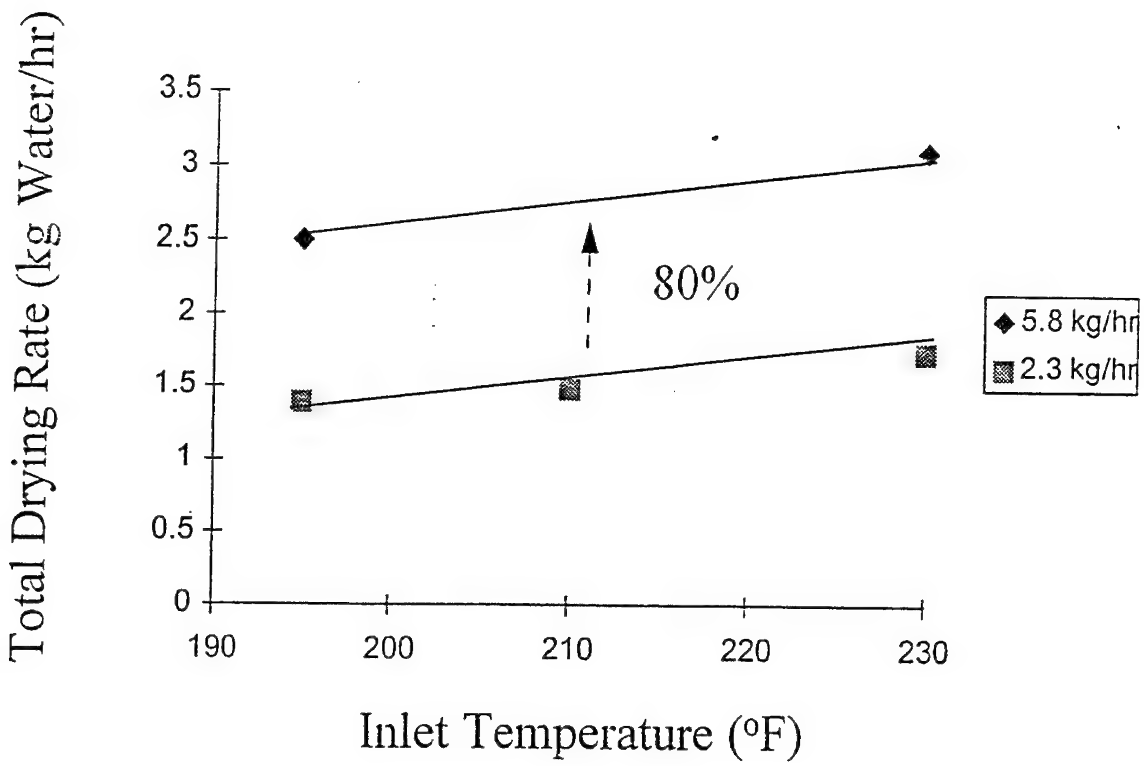

FIGURE 10 - TEMPERATURE VS. TOTAL DRYING RATE

per hour for each degree F increase in the inlet air temperature. There is an 80% increase in the total drying rate that results from the 150% increase in feed rate.

The effect of the controlled operating parameters on the relative difference in the color of the dried carrots and the control sample was determined. The results showed an insignificant effect on the "a" (red/green) and "b" (yellow/blue) values. The "L" (light/dark) parameter correlated with the inlet temperature with a 90% confidence level. The model showed that, the higher the temperatue, the more negative the relative difference in the "L" value. This imples that as the temperature increases, the dry carrots become darker than the control samples.

Neither the rehydration ratio nor the relative difference in the water content of the dry product from the frozen product showed significant correlations with the three controlling parameters. However, the rehydration ratio is a strong function of the final moisture content as shown in Figure 11. This is because all dry carrots rehydrated back to approximately 75% of the original water content, regardless of the final moisture content.

Peas and Potatoes

Base on the drying rate ratio constants, the coefficients of the predictive model parameters for the total drying rate of peas and potatoes were calculated and are summarized in Table 13.

Table 13 - Pea and Potato Drying Models

Variable	Pea ($k_{VC} = 0.77$)	Potato (k_{VC}) = 0.63)
Intercept	+ 0.1344	+ 0.1514
Inlet Temperature (F)	+ 0.0023	+ 0.0007
Feed Rate (g/min)	-0.0023	+ 0.0004
% Open $^{0.5}$	0.0085	0.0047

The applicability of the models was tested by first determining the operating conditions necessary to achieve the desired final moisture content of the dried product. Using the model, combinations of practical operating conditions were then set and experiments were performed at these conditions. The comparative results are summarized in Table 14.

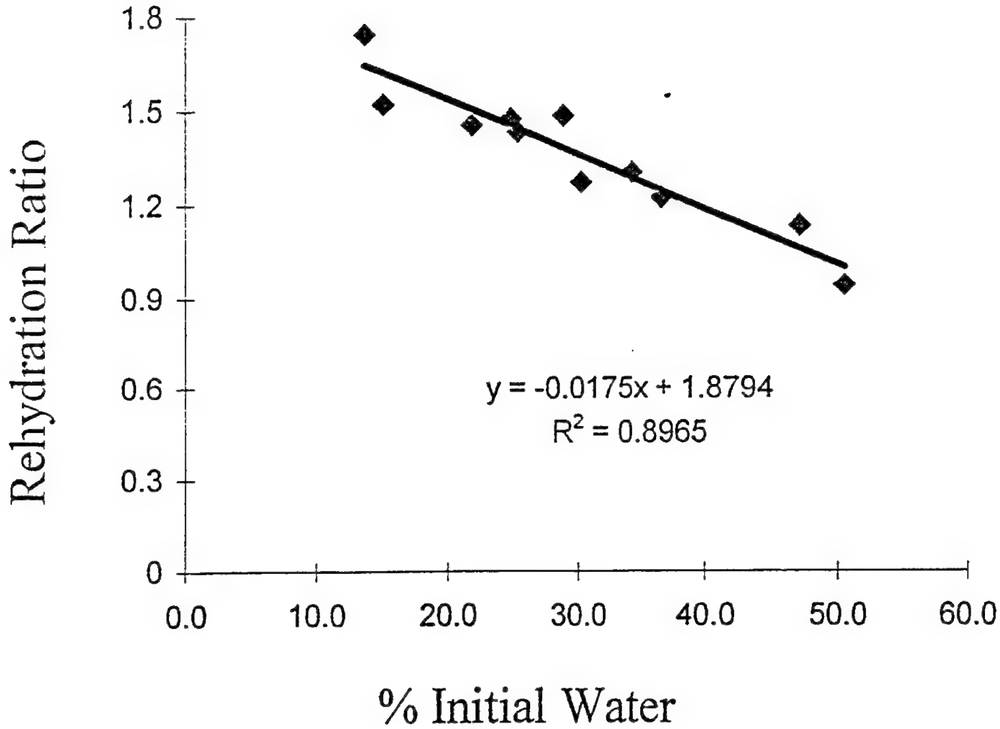

FIGURE 11- REHYDRATION RATIO VS. % INITIAL WATER

Table 14 - Drying Models vs. Experimental Results: Peas and Potatoes

Product	Temp. C	Temp. F	Feed/min g	Feed/min lb	Valve % Open$^{0.5}$	% Water Removed Exp.	% Water Removed Model	% Difference
Pea 1	102	215	25	0.06	10	0.81	0.65	-19.7
Pea 2	102	215	65	0.14	5	0.74	0.52	-30.4
Potato 1	113	235	35	0.08	10	0.57	0.5	- 4.8
Potato 2	102	215	40	0.09	5	0.50	0.47	- 6.1

Discussion

Product Drying Rate Studies

The drying rate curve for carrots as shown previously in Figure 4 can be divided into two drying regimes. On the right, the drying rate is relatively constant with decreasing moisture content, which is consistent with surface evaporation of free water coating the vegetable surface. After a certain fraction of water has been removed, the drying rate is observed to decrease with water content. This reflects internal diffusion control on the overall drying rate, in which the migration of trapped water from the inside of the particle to the surface becomes the rate-limiting step. As the water content decreases, the thickness of the dry layer surrounding the wet core increases, further slowing transport.

The two drying regimes were observed for each of the three vegetables in Figure 5. The pea drying curve shows a smaller evaporative regime than that of carrot or potato. Peas differ from the other two vegetables as it has a skin which would make diffusive resistance important earlier. Differences in the final rates can be attributed to surface area differences among the vegetables.

During the diffusion-controlled drying regime, the drying rates for peas and potatoes remain significantly lower than that for carrot. An additional factor affecting water vapor diffusion is case hardening, in which the dry outer layer forms a hard shell around the inner material, reducing the permeability of the sample. The shell persists for the remainder of drying, leaving a sphere of approximately the same size as the original sample but surrounding a core of mostly empty space. This has been observed visually for peas and diced potatoes, but not for carrots, as shown by the correspondingly higher drying rate for carrots in the diffusion-limited regime.

Ball Dryer Characterization

A mass balance of the empty ball dryer indicates that 12% of mass is lost to air leaks in the system. Air leaks were observed throughout the connections of the dryer, particularly around the bottom of the vessel. The amount of air and water lost should be comparable, however, the water loss was twice that of the air loss. The difference can be partially explained from the sensitivity of the humidity determination to experimental errors, as well as the low water flow rates being measured.

The energy loss in the empty system was 31% of the total energy input. Energy losses can be attributed to conduction and radiation from the stainless steel wall and those associated with mass loss. The power loss not due to air leaks is approximately 2 kW for both empty and product-loaded systems. The heat loss from the dryer surface was estimated at 1.4 kW based on the free convection model. In addition, the radiative losses were calculated at 0.4 kW using the standard blackbody model, closing the mass balance to better than 95%.

The maximum drying capacity was determined to 6.8 kg (15.0 lb) moisture per hour with a 65 C (149 F) temperature drop. This is equivalent to drying 8.6 kg (19.0 lb) of frozen carrots to the 10% final moisture content per hour. The drying capacity calculated here is significantly less than what has been reported by the manufacturer who claimed a 25 kg (55 lb) moisture per hour drying capacity with 55 C (131 F) temperature drop for the same ball dryer. Part of the difference is that we consider two phase transition, melting and evaporation.

The steady-state experiments show similar results of mass and energy losses as with the empty system. The small difference in energy loss can be explained by the fact that the temperature of the steady-state system is slightly lower than that of the empty system. This results in lessening the heat lost through natural convection, and decreasing the energy loss in the steady-state run relative to the empty run.

Statistical Design Experiments

The final moisture content of the dried carrots ranged from 13.6 to 47.1% corresponding to 84.8 and 47.6% water removal, respectively. The expected general trends were observed for all three controlling parameters. Drying increased with inlet temperature. The feed rate is directly proportional to the final percent moisture of the dried products. Increasing the exhaust valve opening increased the amount of drying.

The feed rate affects a number of parameters. Increasing the feed rate raises the evaporative load and reduces the average system temperature. Associated with this is also an increase in the relative humidity of the air, which lowers the concentration driving force. As the product feed rate increased, while all other control variables were held constant, the exhaust temperature was observed to decrease. The lower average system temperature reduced the single particle drying rate causing the final water content to be higher.

However, it is incorrect to conclude that the overall system drying rate is reduced as the feed rate increases. Although the final percent water is higher, because of the greater feed rate, the overall drying rate (Equation 8) can still increase.

$$\text{Drying Rate} = (\text{Feed Rate})\ (\%\ \Delta\ \text{water}) \qquad (8)$$

As shown in previously in Table 6, typically the overall drying rate was greater with vegetables of higher final moisture content. This was shown explicitly in

Figure 12 for carrots. This relation is expected since the specific drying rate is greater at high moisture contents as shown in Figures 3 and 4. Thus, there is clearly a trade-off between drying efficiency and final moisture content.

The position of the exhaust valve can also affect the drying process. By opening up the valve, more air is allowed to flow from the bottom to the top of the bed, improving the mass transfer coefficient. For example, by opening up the exhaust valve from 25 to 100%, the final moisture content reduces by a range of 3 to 5% which is consistent with air flow rate data (Table 3).

The experimental results for peas and potatoes reflect the same trend of increasing darkness with increasing percent moisture removal as shown for carrots. Peas show a slight decrease in "L" value with drying relative to the control (see Table 7), while potatoes show a large decrease from 67 to 60% as shown in Table 8. This larger degree of darkening is due to the larger amount of starch in potatoes, which like toasted bread, browns in the presence of heat. The residence time characteristics of peas and potatoes were also similar to carrots, although some larger potato pieces were caught in the sieve and recircuated through the ball dryer, leading to additional drying and browning.

Comparison of Drying Rate to Ball Dryer Results

A model can be developed to predict product moisture content as a function of residence time, by combining the drying rate results from the moisture analyzer with the operating conditions. A two-regime model can be applied to drying of carrots from 89 to 13% if it is assumed that the drying kinetics observed determined in the moisture analyzer are similar to those expected in the ball dryer. For the initial phase, carrots are dried from 89 to 55% moisture at a constant rate of 3.5 % moisture removed (Figure 3). At this rate, 9.7 minutes are required to dry the carrots to 55% moisture. Taking an average of 2.4% moisture removed for the drying rate during the diffusion-limited regime, an additional 18.8 minutes of drying time is needed to dry the product to 13% moisture. The total residence time for drying of 28.5 minutes is still less than the 50 minute residence time observed in the dryer. This difference may be due to the fact that the relative humidity of the air in the dryer is greater than that in the moisture analyzer.

Model Prediction

The model underpredicted the percent water removal by a range of 20 to 30% for peas. The shear and compression forces experienced between the balls may squeeze additional free water out of the pea interior and also cause the skin to rupture. This water can then be removed by evaporation rather than diffusion through the hard shell as in the moisture analyzer.

The percent water removal for potatoes showed good agreement with the model, agreeing within about 5% for two trials. The potato pieces were larger in size and did not shrink significantly with drying. As a result, some product pieces did not

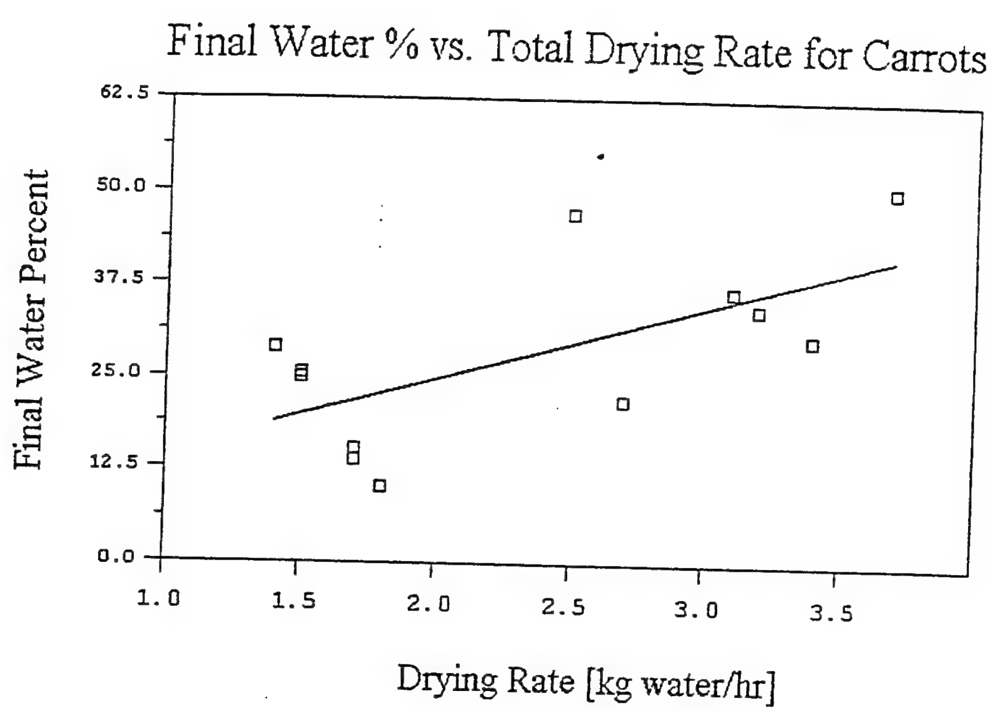

FIGURE 12 - FINAL WATER % VS. TOTAL DRYING RATE FOR CARROTS

pass through the sieve and were brought back up with the ball screw for a second pass through the dryer. These pieces were clearly burnt upon collection, and most were removed from the analytical samples by inspection. The overall residence time for the potato samples may have been somewhat longer because of this size issue, which would lead to slightly higher moisture removal relative to carrots.

Economic Analysis

The cost/benefit analysis was based on estimates done by the MIT Practice School (Langner, et al, 1995). A 15% discount rate and a 15 year process lifetime were used to calculate the net present value of fixed cost. The total cost of water removed at the drying capacity rate of 1,000 lb (454 kg) of water per hour for the ball dryer and for the freeze dryer were estimated to be $7.77 and $37.27 per kg ($3.53 and $16.94 per lb), respectively. However, based on the operating capacity and the quality of dry product analysis for the ball dryer, there are limitations in drying the product to low moisture content. Hence, the cost analysis, which originally was designed for ball drying of frozen peas from 78% initial to 3% final moisture content was modified to estimate the cost for a two-step drying process. The drying process comprises using the ball dryer for 80% of the total drying and the freeze dryer for the remaining 20%. This would dry the peas from 78% to 18% in the ball dryer, and remove remaining water with the freeze dryer.

The total cost of the two-step drying process was estimated to be $42.50 per kg ($19.32 per lb) of water removed, which is slightly greater than the freeze drying process alone. However, this analysis was based on the scenario that the manufacturer is starting up a new plant where both the freeze dryer and ball dryer have to be purchased. The breakdown of the cost structure is different when comparing the freeze dryer and the two-step drying process. By substituting the ball dryer as a first step drying stage, the utility cost decreases by almost 70% when compared to freeze drying alone. The decline in utility costs is offset by the increase in capital cost plus additional costs such as maintenance and depreciation. It should also be noted that the cost associated with the change in the quality of the product when using the ball dryer was not included in the economic model. Further economic analysis based on the scenario where the manufacturer is already operating a freeze dryer was investigated. By using the ball dryer as a first stage dryer, the cost of moisture removal reduces from $37.37 to $13.55 per kg ($16.94 to $6.16 per lb of water. From a manufacturing standpoint, the cost of using the ball dryer can be justified if it can be partially utilized for drying some products as a one step drying process. In addition, the feasibility of the ball dryer is strongly dependent on the annual capacity. A realistic evaluation of processing requirements should be the next step in assessing the potential of using the ball dryer system.

Product Quality Issues

Samples which were dried to a low final moisture content exhibited some degradation of product quality. The two major forms of damage observed were due

to heat and mechanical degradation. High heat exposure affected the color, rehydration behavior and appearance of the sample. The high temperatures used to obtain low final moisture content caused a darkening of the product surface. This is quantified in Table 7 where test 3 is a nonsteady-state sample at 10% final moisture. The "L" value for test 3 is 37.8 $\pm$ 0.17, compared to an average of 43.6 $\pm$ 1.1 for other dried samples and 44.7 $\pm$ 0.51 for the control

In addition to discoloration, the physical appearance of the sample is affected during drying. Rehydration of the 10% final moisture sample only increased the moisture to 71%, compared to 76% for the other ball dried samples and 87% for a freeze dried sample, indicating that ball drying in general has a harmful effect on the cellular ingegrity which increases with temperature. Some degree of degradation also occurs as the product is exposed to the high temperatures and abrasive conditions inside the ball dryer. When dried to low levels of moisture, the rehydrated sample appears wrinkled and unappetizing

A sample of each of the three vegetables investigated in the ball dryer was prepared as a control by freeze drying. The product quality exhibited by the freeze dried samples upon rehydration was high. The carrots rehydrated to 86% in the two minute test, nearly attaining the original level of 89%. The flavor, appearance and texture was nearly identical to that of the original diced carrot when boiled for two minutes. The color parameters in Table 7 closely match that of the control. Similar results were obtained for peas and potatoes.

Foods dried at high levels in the ball dryer would not be preferred to freeze dried samples, based on quality. Ball drying is unsuitable when the product appearance is very important such as when used as is. If a dried vegetable is to be part of a mixed food product in which each component is not viewed individually, such as a stew or burrito, then appearance may not be as critical and ball drying may substitute for most, or even all, of freeze drying. Ball drying is ideal for dried products destined for mixing with other ingedients, as in sauces or seasonings, or for products to be flaked as in current applications with fish hydrolysates or taro starch, or for vegetables for soups, stews and casseroles, i.e. mushrooms, bell peppers and scallions.

Conclusions

The Precision Ball Dryer™ was fully characterized and the practical limitations to its use were determined. Predictive models were developed and tested for carrots, peas and potatoes. The energy loss of the ball dryer system is 30%, with air leaks accounting for 10%. Free convection from the dryer surface and radiation accounts for the other losses. The maximum drying capacity of the system is 6.8 kg (15.0 lb) of moisture removed per hour, substantially less than specified by the manufacturer.

The practical limitations were identified to ensure continuous operation. The ball screw speed was set at its lowest level, 1.2 RPM, to maximize residence time. Ambient humidity limited the inlet temperature. A predrier for the inlet air may

help efficiency in ambient humid conditions. This was set to a practical maximum of 110 C (230 F). The feed rate must be < 96 g (0.21 lb) per minute to prevent clogging in the feed neck. The drying capacity is defined by the preceding parameters. The exhaust valve position must allow for transport of dried product, but this wasn't a limitation. The best operating conditions are at 100% open to maximize air flow rate through the drying bed.

A factorial designed set of experiments was performed within the process limits to develop an empirical drying model based on temperature, feed rate and exhaust valve opening. The best fit was obtained with linear coefficients. The interactions among the factors were not important. An improved fit was obtained when using the valve position to 0.5 power, as supported by the forced convective heat and mass transfer correlations. The percent moisture removal was found to be a strong function of the inlet temperature and feed rate, and a weak function of valve postion. The model was found to predict the final moisture content to within 2% for carrots. The predictive model was extended to other vegetables through the use of a scaling factor that was derived from drying rate studies. This model predicted the final moisture content of potatoes well, but underestimated peas by 30%.

Based on model predictions and product quality issues, the ball dryer is ideally suited to be the first stage of a two-stage food drying process, with freeze drying used for the final drying. The optimal level of ball dryer use is based on the tradeoff between product quality and economics for a given food product. An economic analysis shows that the operating costs are 70% less for the two-stage process, but the overall economic viability is strongly dependent on the volume processed.

Recommendations

- Use of the ball dryer as the first stage of a two-stage drying process with freeze drying as the second stage should be pursued.
- Sensory testing on dried products should be included as an additional measure of product quality
- The economics of the ball dryer should be further investigated. Issues include an accurate measure of annual capacity and a sensitivity analysis with respect to the cut-off level of a two-stage drying process.
- Use of the ball dryer for other foodstuffs using the approach developed in this report should be explored.
- A predryer should be installed to reduce the moisture content of the inlet air to increase efficiency and reduce variation due to ambient humidity fluctuations.

This document reports research undertaken at the U.S. Army Soldier Systems Command, Natick Research, Development and Engineering Center and has been assigned No. NRDEC/TR-96/014 in the series of reports approved for publication.

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Appendix - Analytical Equipment and Procedures

Moisture Analysis

The primary measure of product quality was the percent of moisture remaining in the dried product. This was measured using a Computrac Moisture Analyzer™ which weighs the sample before and after heating it at a constant temperature to obtain percent moisture data. First, an empty sample plan is placed in the instrument which weighs and tares the pan mass. Approximately 5 g (0.2 oz) of sample is added and the analyzer automatically begins heating. All ball dryer product samples were measured at 66 C (150 F). This temperature is maintained until the rate of mass change slows, indicating nearly complete drying. This automatically shuts off the heat before the onset of charring, which would introduce additional mass loss due to combustion; the sample is dark and hard after drying but not burnt.

Drying Rate

A sample of frozen product was placed in the Computrac™ using the normal procedure. The sample temperture was set to 80 C (175 F) and the percent moisture display on the analyzer was recorded every minute until drying was completed. The rate of drying was calculated from the percent moisture data. This data could then be plotted versus either the percent total moisture content or the percent free moisture content, obtained by dividing by the initial moisture content obtained at the end of the run.

Colorimetry

The spectrophotometer was first calibrated with a standard white sample. The glass sample dish was then filled with about 50 g (0.11 lb) of rehydrated sample, enough to fill it at least halfway. Any void pockets between pieces must be eliminated, so the sample was compacted by pressing until a uniform packing was observed from beneath the dish. The sample reading was taken three times with stirring and compaction of the sample between readings to obtain an average value for the entire sample.

Texture Analysis

This work was performed on an Advanced Texture Analysis™ system. The test was performed for peas by placing four peas in a row beneath a single test blade. The blade was then moved at a speed of 0.5 mm (0.02 in) per second over a distance of 15 mm (0.6 in), crushing and shearing through the peas. A plot of the force over distance travelled is produced from which the peak force, measured in Newtons, can be determined. For carrots and potatoes, pieces were trimmed to nearly the same size as the peas and tested four at a time.